Water Hammer Analysis by use of Superposition Principle

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Abstract

Very strong pressure pulses or surges, also referred to as water hammer; often occur in fluid-conducting pipes. A water hammer event or hydraulic transient results when the velocity of flow changes in a pipeline that can cause extreme damage and burst in pipes. So it is important to analyse water hammer phenomenon accurately in pipelines. In many cases the main liquid transmission line conducts the fluid from several plants which feed the main line in different points. In such cases if the water hammer phenomenon occurs due to the valve closure or pump failure, the amount of pressure pulses that created by it are complicate to be calculated and need a simplification. So the main objective of this paper is to reperesent the application of superposition principle in water hammer analysis of a main pipeline which is fed with several branch pipes. After the introduction of water hammer concept and equations in this paper, the superposition method are explained. In the last part a case study in one of Iranian oil fields is presented in details. The results show a near estimation of real results. So the principle of superposition can be an acceptable method for water hammer analysis in multiple branches pipelines.

Key words: water hammer, surge, superposition, pressure pulse

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1. Introduction

Devices such as valves, pumps and surge protection equipment exist in a pipe network. Power failure of pumps, sudden valve actions, and the operation of automatic control systems are all capable of generating high pressure waves in domestic liquid supply systems. Water hammer or pressure surge is a type of hydraulic transient that refers to rapid changes of pressure in a pipe system that can have devastating consequences, such as collapsing pipes and ruptured valves [1, 2].

Consider a long pipe (AB) connected at one end to a reservoir containing water and a height (H) from the center of the pipe. At the other end of the pipe, a valve is provided to regulate the flow of water.

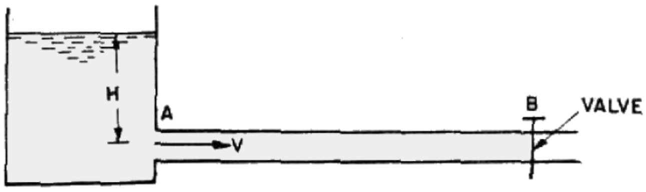


Figure 1: A water reservoir with a valve to regulate the flow.

If the valve is suddenly closed, the flowing water will be obstructed and momentum will be destroyed and consequently a wave of high pressure will be created which travels back and forth starting at the valve, traveling to the reservoir, and returning back to the valve and so on. This wave of high pressure has a very high speed which may reach the speed of sound wave and may create noise and has an effect of hammering action on the walls of the pipe, so hence is commonly known as the water hammer phenomenon [5].

2. Analysis of Water Hammer [4, 6]

The pressure rise due to water hammer depends upon the velocity of the flow of liquid in pipe, length of pipe, time taken to close the valve and elastic properties of the material of the pipe.

If the valve closed suddenly, Joukowsky's formula which originates from Newton's laws of motion, describes the pressure change that results from a rapid change in velocity.

$$\Delta H = \frac{aV_0}{g} \tag{1}$$

Where "a" is the speed of pressure wave that is depend on the pipe wall material and the properties of the fluid.

$$a = \sqrt{\frac{E}{\rho}} \tag{2}$$

$$\frac{1}{E} = \frac{1}{E_f} + \frac{D}{E_p e} \tag{3}$$

For the case that the valve closed gradually, below equation describes the pressure change.

$$\Delta H = \frac{LV_0}{gt} \tag{4}$$

By analyzing the above formula, it is clear that the larger the magnitude of the velocity change and the larger the magnitude of the wave speed, the greater the change in pressure will be.

The time required for the pressure wave to travel from the valve to the reservoir and back to the valve is:

$$T = \frac{2L}{a} \tag{5}$$

If the closure time of valve be less than the wave travel time (*T*), it is considered suddenly. But if the closure time of valve be more than the wave travel time, it is considered gradually.

3. Superposition Principle [3]

The analysis of the water hammer phenomenon as presented earlier in this paper appear to be applicable only for describing the pressure pulses in pipelines with one source of fluid that was pumped by a constant rate. Since real transportation systems may have several sources that feed the pipelines at different point, a more generalized approach is needed to study the fluid flow behavior during the flow shut in.

The principle of superposition is a powerful concept that can be applied to remove the restrictions that have been imposed on water hammer analysis in multiple branch pipes. The superposition theorem states that the sum of pressure pulse due to individual flow rates is equal to total pressure pulse due to all flow rates. This concept can be applied to account for a main pipeline which is fed at some different point.

$$\Delta P_{total} = \Delta P_1 + \Delta P_2 + \dots \tag{6}$$

4. Case Study

In this part, the water hammer phenomenon in one of plant of Iranian Oilfields is analyzed. In this plant the main pipeline that conducting crude oil from plant, are fed in five points. Also the diameter of the main line changes at a distance away from the plant.

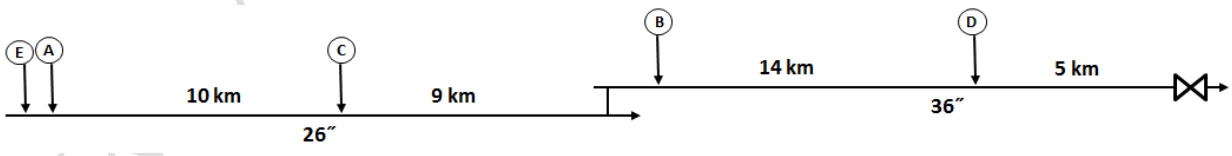
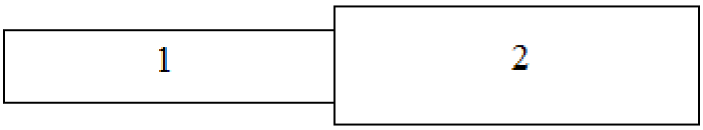


Figure 2: A schematic of multiple branch pipe line in case study.

The procedure to convert the series pipe to an equivalent uniform pipe:



$$\frac{L}{a} = \frac{L_1}{a_1} + \frac{L_2}{a_2} + \dots\dots + \frac{L_n}{a_n} = \sum \frac{L_n}{a_n} \tag{7}$$

The properties of pipes and flowing fluid are given in the following tables:

Table 1: Fluid and pipe properties in case study.

E_f (N/m^2)	E_p (N/m^2)	*e* (mm)	ρ (kg/m^3)	D_1 (in)	D_2 (in)	L_1 (km)	L_2 (km)
1.66E+09	210E+09	95	850	26	36	19	19

Table 2: Fluid flow data in main pipeline feed points.

P.U	Q (STBD)	Q (m^3/sec)	V (m/s) $_{26''}$	V (m/s) $_{36''}$
A	53431	0.09833	0.287263	0.149825
B	162128	0.2983	–	0.454518
C	90162	0.1659	0.484663	0.252781
D	59320	0.1091	–	0.166235
E	79749	0.14676	0.428747	0.223617

By using equations 2, 3 and table 1, the speed of pressure wave in the main pipeline and therefore the time required for the pressure wave to travel from the valve to the feed points and back to the valve can be calculated.

Table 3: Segments length and wave speed.

P.U	L_1 (m) $_{26''}$	L_2 (m) $_{36''}$	a_1 (m/s) $_{26''}$	a_2 (m/s) $_{36''}$	L/*a* (sec)
A	19000	19000	1122.6509	1053.1226	34.9658
B	–	19000	–	1053.1226	18.0416
C	9000	19000	1122.6509	1053.1226	26.0583
D	–	5000	–	1053.1226	4.7478
E	19000	19000	1122.6509	1053.1226	34.9658

- (Note: The valve time of closure is 120 sec)

Table 4: The case of closure for each segment.

P.U	T = 2L/*a* (sec)	t_{valve} > T	t_{valve} < T	Valve closure is:
A	69.932	✓	×	gradually
B	36.083	✓	×	gradually
C	52.117	✓	×	gradually
D	9.496	✓	×	gradually
E	69.932	✓	×	gradually

In according to the valve closure case (suddenly or gradually), equation 1 or 4 can be used to evaluate the pressure pulse which is created by each segment. As the superposition principle say, the total pressure pulse which is created in the system, is the sum of each segment pressure pulse (equation 6). The results of calculations are shown in table 5.

Table 5: Each segment pressure pulse.

P.U	**L** *(m)*	**V** *(m/s)*	**ΔH** *(m)*	**ΔP** *(KPa)*	**ΔP** *(psi)*
A	38000	0.218544	7.06178	58.82468	8.5362
B	19000	0.454518	7.34339	61.17051	8.8766
C	28000	0.327314	7.79319	64.91731	9.4203
D	5000	0.166235	0.70678	5.887488	0.8543
E	38000	0.326182	10.53989	87.79732	12.7405

$$\Delta P_{total} = 40.428\,psi, \quad \Delta P_{total} = 278.597\,kPa$$

The recorded pressure behind the valve shows a value of 44 psi increase in pressure during the water hammer phenomenon.

5. Conclusion

- In this paper the analyses of water hammer phenomenon in a system that have multiple source of flow have been done by use of super position principle.
- By the super position principle the effect of each source of flow take into account separately.
- The total pressure pulse due to water hammer is the sum of pressure pulses which are created by each flow points.
- More accurate and more acceptable pressure pulse calculation method is utilized in this study and the final results confirm this assertion.

Nomenclature

L	*length of the pipe (m)*
a	*velocity of pressure wave (m/sec)*
ρ	*fluid density (kg/m^3)*
E_f	*bulk modulus of elasticity of fluid (N/m^2)*
E	*effective bulk modulus of fluid in elastic pipe (N/m^2)*

E_p	*Modulus of elasticity of the pipe material (N/m^2)*
e	*thickness of pipe wall (inch)*
D	*diameter of pipe (inch)*
V_0	*Initial velocity of fluid flowing in the pipe before pipe closure (m/sec)*

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